5.4 Nuclear Decay

This topic covers radioactive decay.

This topic may be studied using applications that relate to, for example, medical physics and carbon dating.

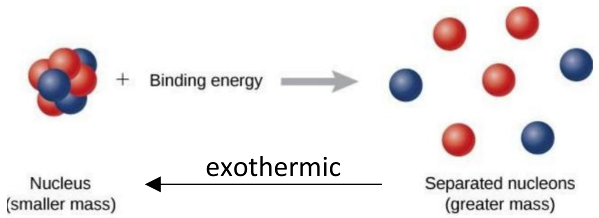
This unit includes many opportunities for developing experimental skills and techniques by carrying out more than just the core practical experiments.

Candidates will be assessed on their ability to:

133 understand the concept of *nuclear binding* energy and be able to use the equation $\Delta E = c^2 \Delta m$ in calculations of nuclear mass (including mass deficit) and energy

When measuring the mass of a nucleus and the mass of its constituents,
"the measured mass of a nucleus is always less than the sum of the masses of its constituent nucleons"
This difference is known as the **mass defect / mass deficit**
- At the nuclear level, mass and energy are interchangeable and can be related by the equation, which applies to all energy changes: $\Delta E = c^2 \Delta m$
- Hence, the mass that is "lost" is converted into energy and released when the nucleons fuse to form a nucleus
- This energy is known as the *binding energy*

The **nuclear binding energy** is
- *the energy required to separate the nucleus into its constituents/ nucleons* (or)
- *the energy released when a nucleus is formed from its constituents*



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134 use the *atomic mass unit (u)* to express small masses and convert between this and SI units

The change in mass when nucleons fuse is incredibly small, so when measuring the mass difference, atomic mass units (u) are used
"One atomic mass unit (1*u*)
= 1/12th the mass of a carbon-12 atom
= 1.66 x 10^{-27} kg"

A change in 1*u* of mass means that 931.5 MeV of energy is released

Particle	Mass / u
Proton	1
Neutron	1
Electron	0.0005
Alpha (α)	4

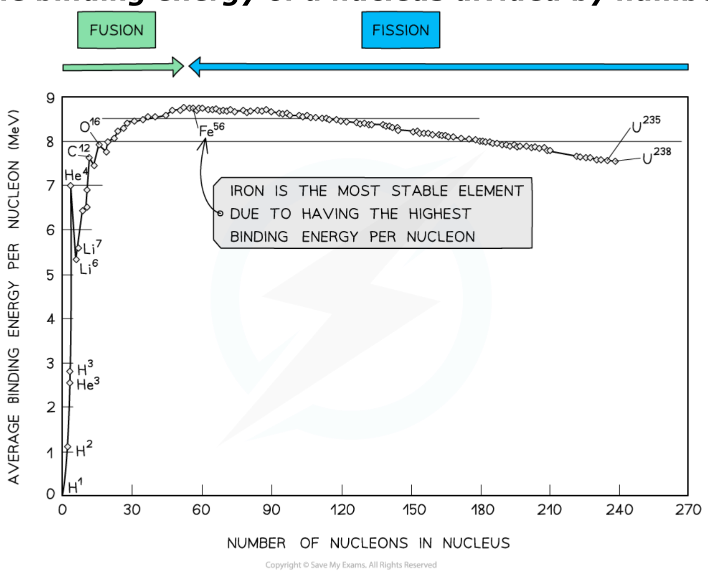
135 understand the processes of nuclear fusion and fission with reference to the binding energy per nucleon curve

Nuclear fission is
- the splitting of a large, unstable nucleus into two smaller daughter nuclei
- Occurs in very large unstable nuclei (such as uranium, plutonium)
- Occurs completely randomly (spontaneous fission)
- Can also be induced (by absorbing a neutron)
- Energy is released during fission because *the smaller daughter nuclei have a higher binding energy per nucleon*

Nuclear fusion is
- *the joining up of two smaller nuclei to form one larger (heavier) nucleus*
- Only occurs in fairly small nuclei
- Requires extremely high temperatures (for eg. in stars)
- Energy is released during fusion as the *larger nucleus has a much higher binding energy per nucleon*
- Fusion releases far more energy than fission
- Fuels for fusion are more plentiful
- Products of fusion are much less radioactive

In both processes, nuclear binding energy increases as it releases energy

Binding Energy per Nucleon is defined as:
"The binding energy of a nucleus divided by number of nucleons in nucleus"



A higher binding energy per nucleon indicates a higher stability since it requires more energy to pull the nucleus apart

Graph does not start at 0 as this is not a nucleus

136	understand the mechanism of nuclear fusion and the need for very high densities of matter and very high temperatures to bring about and maintain nuclear fusion

In the fusion process,
the mass of the new heavier nucleus is less than the mass of the constituent parts of the nuclei fused together, as some mass is converted into energy
Not all this energy is used as binding energy for the new larger nucleus, so energy will be released from this reaction
The binding energy per nucleon afterwards is higher than at the start

Conditions for fusion

1. **Very high temperatures (to bring about fusion)**
   - This is because a massive amount of energy is required to overcome the electrostatic force of repulsion between nuclei, as nuclei are all positively charged
   - In stars, the very high temperature in the core provides high enough kinetic energy for positively charged nuclei to get close together enough to fuse
2. **Very high densities (to maintain fusion)**
   - This is to make sure that there are enough colliding protons undergoing fusion (to ensure high collision rate between nuclei/ protons)

137	understand that there is background radiation and how to take appropriate account of it in calculations

Background radiation is defined as:
*"**Radiation which are always present around us (from no obvious source)**"*
- Radiation is measured in counts per second in a unit called Becquerel (Bq)

	- Background radiation can come from natural or man-made sources - Examples: 1. Radon gas - which is released from rocks and soil (most plentiful) 2. Artificial sources - nuclear weapons testing and medical sources 3. Cosmic rays from space 4. Rocks containing naturally occurring radioactive isotopes Background radiation is around us constantly, so when taking readings of the count rate of a radioactive source it is important to measure the background radiation first, then subtract this value to find the corrected count, which is the actual count rate caused by the source Some factors that affect background count rate: 1. The place where the measurement is made 2. The time interval (How long the measurement was made) 3. Type of detector used (some detectors are more sensitive than others)

138	understand the relationships between the nature, penetration, ionising ability and range in different materials of nuclear radiations (alpha, beta and gamma)

Radiation	**Alpha α**	**Beta β^-**	**Gamma γ**
Nature	Helium nucleus (2 protons + 2 neutrons) $^4_2\alpha$	High energy electrons (produced in a nuclei when a neutron changes into a proton & an electron) $^0_{-1}\beta$	High energy electromagnetic waves $^0_0\gamma$
Penetration	Stopped by paper	Stopped by a few mm of Aluminium	Reduced by a few mm of lead or several metres of concrete
Ionising Ability	High	Moderate	Low
Range in air	2-10 cm	Around 1m	Infinite (follows inverse square law)
Mass	4u	0.0005u	0
Charge	+2	-1	0
Speed	0.05c	Less than 0.99c	1c

139	be able to write and interpret nuclear equations given the relevant particle symbols

Alpha Emission	Beta Emission	Gamma Emission
$^A_ZX \rightarrow {}^{A-4}_{Z-2}Y + {}^4_2\alpha$ $^{212}_{84}Po \rightarrow {}^{208}_{82}Y + {}^4_2\alpha$	$^A_ZX \rightarrow {}^A_{Z+1}Y + {}^0_{-1}\beta$ $^{14}_6C \rightarrow {}^{14}_7N + {}^0_{-1}\beta$	MASS NUMBER STAYS THE SAME $^A_ZX \rightarrow {}^A_ZX + {}^0_0\gamma$ ATOMIC NUMBER STAYS THE SAME

140	**CORE PRACTICAL 15: Investigate the absorption of gamma radiation by lead**
141	understand the spontaneous and random nature of nuclear decay

Radioactive decay is defined as:

"The spontaneous disintegration of a nucleus to form a more stable nucleus, resulting in the emission of an alpha, beta or gamma particle"

- Radioactive decay is a random and spontaneous process meaning you can't predict when the next decay will occur
- Spontaneous means it is not influenced by environmental factors
- Random means exact time of decay cannot be predicted

However, a given radioactive nucleus will have a constant decay probability (λ) known as the *decay constant*, which is the *probability of a nucleus decaying per unit time*

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be able to determine the half-lives of radioactive isotopes graphically and be able to use the equations for radioactive decay

activity $A = \lambda N$, $\frac{dN}{dt} = -\lambda N$, $\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$, $N = N_0 e^{-\lambda t}$ and $A = A_0 e^{-\lambda t}$ and derive and use the corresponding log equations.

Decay constant can be calculated by finding the change in the number of nuclei (ΔN) of a sample over time (Δt), over the initial number of nuclei (N)

$$A = \frac{\Delta N}{\Delta t} = \lambda N$$

Where N = number of nuclei remaining in a sample

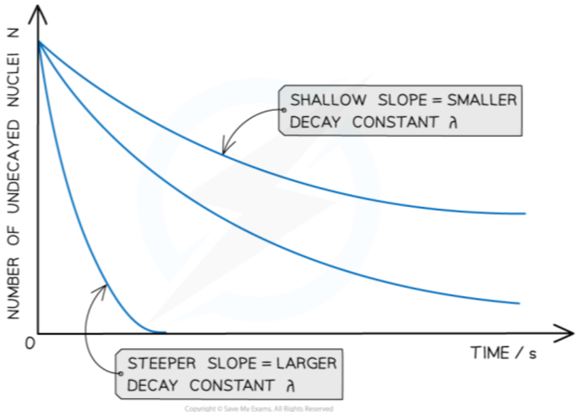
Since activity = number of decays per unit time, an activity of 1 Bq is equal to one decay per second, or 1 s^{-1}

!Note there is a minus sign like this $A = -\lambda N$ *which indicates that the number of nuclei remaining decreases with time*

$$\text{Number of nuclei} = \frac{\text{mass} \times N_A}{\text{molecular mass}}$$

where N_A is avogadro's constant

Exponential Decay



$$N = N_0 e^{-\lambda t}$$

Where:

N_0 = the initial number of undecayed nuclei (when t = 0)

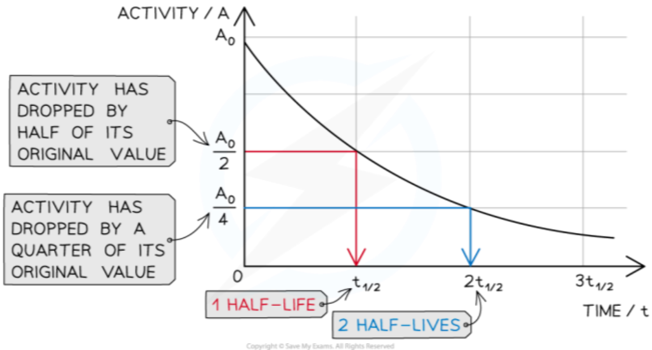
λ = decay constant (s^{-1})

t = time interval (s)

$$A = A_0 e^{-\lambda t}$$

Half-Life is defined as:

"The time taken for half the number of nuclei in a sample to decay" or ***"the time taken for the activity of a sample to halve"***



$$\lambda = \frac{\ln 2}{t_{1/2}}$$